

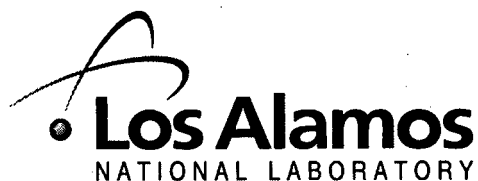
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# ON THE X-RAY EMISSION FROM THE RADIO SOURCE SGR A\*

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## Abstract

Recent infrared observations of the Galactic Center have permitted the estimation of orbital parameters for the 8 O stars closest to the compact, nonthermal radio source, Sgr A\*. The emission of Sgr A\* is thought to be due to the accretion of gas down the potential well of a  $\sim 3 \times 10^6$  solar mass black hole at the dynamical heart of the Milky Way. The O stars are located within 0.03 pc of Sgr A\* and are likely to have significant stellar winds. Since they are deep within the potential well of a black hole, much of their winds are gravitationally bound. These hot winds may be piling up and emitting significantly in the X-rays. Thus it is possible that the emission from the recently detected compact CHANDRA source may at least in part be due to the winds of these O stars rather than the hot gas close to the event horizon of the black hole. This has serious implications for applicable black hole accretion models. From preliminary 3D numerical simulations which treat the 8 O stars as mass sources moving on individual orbits, we have constructed simulated X-ray images. We present these images and discuss their impact on accretion models for Sgr A\*.

## 1 Introduction

Sgr A\* is a strong, compact radio source located at the dynamical center of the Galaxy. The radio emission is thought to arise from gas falling down the steep potential well of a  $\sim 3 \times 10^6 M_\odot$  black hole (Melia & Falcke, 2001). However, Sgr A\* has not been definitively detected at other wavelengths due to the large

extinction between us and the Galactic Center (GC). It has been expected that there would be significant X-ray emission due to thermal bremsstrahlung and upscattered magnetic bremsstrahlung radio emission (Yuan, Markoff, & Falcke, 2002). Recent CHANDRA X-ray images do indeed show a point source within the  $\sim 1''$  astrometric error box of Sgr A\*. The point source has been seen to flare and is surrounded by diffuse emission in the 2-10 keV CHANDRA band (Baganoff et al., 2001, 2003). The details of the point source have been used to constrain models of the gas accretion onto Sgr A\* (Falcke, K rding, & Markoff, 2004).

## 2 Another possible source of X-rays

There are at least 8 late O stars located within  $\sim 1''$  of Sgr A\* in projection (at 8 kpc, the distance of the GC,  $1'' \simeq 0.04$  pc). However, from IR Keck observations, these stars now have measured orbital parameters (Ghez et al., 2004) and although some have large error bars, they are very likely to be orbiting a point mass of  $\sim 3.5 \times 10^6 M_\odot$ . One star, with an orbital period of  $\sim 15$  yrs, has been seen with an orbital velocity of more than  $2000 \text{ km sec}^{-1}$ ; within a few decades it will serve as a unique test of general relativity due to the precession of its orbit (Weinberg, Milosavljevic, & Ghez, 2004). It is worth noting that some of the stars' orbits are highly elliptical, suggesting recent ejection by the black hole. Clearly, the strong, hot winds of these stars will contribute to the X-ray flux seen by CHANDRA. We ignore here the winds from two dozen WR and early O stars in the IRS 16 and IRS 13 clusters (Geballe, Krisciunas, Bailey, & Wade,

1991); these stars are more than 10 times further away from Sgr A\* and are likely to contribute substantially to the extended CHANDRA X-ray emission (Rockefeller, Fryer, Melia, & Warren, 2004). Since there are so many stars in such a small volume, strong wind collisions and shocks will dissipate sufficient kinetic energy to result in significant X-ray emission. This then begs the question we try to address in this paper: how much of the observed point-source X-ray flux is from close to the event horizon of the black hole and how much is extended emission due to colliding stellar winds?

### 3 Numerical approach

We use RAGE, a 3D Eulerian CAMR code with 2nd order Godunov hydrodynamics and a Riemann solver (Baltrusaitis, R.M. et al., 1996), to make the simulations run more quickly. We used a finest resolution of  $1 \times 10^{15}$  cm. We treat each of the 8 O stars as a moving mass and energy source in a 3D cartesian hydrodynamics simulation. Since the stars are thought to be  $\sim O8$ , we use a mass injection rate,  $\dot{M}$ , of  $2.5 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$  and an energy injection rate of  $81 L_{\odot}$ . This results in a wind terminal velocity of  $\sim 2200 \text{ km sec}^{-1}$ . The injection radius for each star was  $2.5 \times 10^{15}$  cm (5 cells across). Assuming solar abundances and collisional ionization equilibrium, we then perform a radiative transfer calculation to produce synthetic X-ray images, spectra, and luminosities at various simulation times.

#### 3.1 Included physics

We include not only the gravitational potential from a  $3.5 \times 10^6 M_{\odot}$  point mass but all that from the underlying (and unseen) stellar cluster. We assume the gas is optically thin so that we can include radiative cooling as a simple energy sink. We use the thermal plasma code MEKAL, (Mewe, Gronenschild, & van den Oord, 1985) as distributed in XSPEC to calculate the cooling rates. We solve for the location and velocity of each star each time step and inject the appropriate mass and thermal energy with a momentum that matches the stellar velocity. We use outflow boundary conditions so as to permit unbound gas to escape the volume of solution. The projected orbits of the 8 O stars are shown in Fig. 1. Three stars have open orbits since their periods ( $> 10^4$  yrs) are longer than the length of the simulations. Nonetheless, if required, these stars are al-

lowed to enter and leave the grid. Although there is a slight bias in their apoapses (Ghez et al., 2004), the 8 stars do not define a clear, constant angular momentum vector, so it is interesting that the black hole is inferred to have a very large angular momentum (Aschenbach, Grosso, Porquet, & Predehl, 2004). Although collisions are not included in these simulations, the 8 O stars are close enough to each other at times that stellar encounters may be significant. The ISM is taken to be a  $\gamma = 5/3$  gas with  $n = 10 \text{ cm}^{-3}$  and  $T = 10^4$  K. The injected wind is also assumed to be a  $\gamma = 5/3$  gas.

## 4 Results

### 4.1 Early time results

In Fig. 2 we show the column density along the line of sight at 8 yrs after the start of the simulation. At this time the winds have not yet filled the volume of solution. Also, the stars have not yet moved very far so that individual wind blown bubbles can be seen. The velocity, with the largest vectors corresponding to  $1000 \text{ km sec}^{-1}$ , in the xy plane at  $z = 0$  is overlaid on the this and following figures. Two stars are nearly in the  $z = 0$  plane at this time and are nearly freely flowing into the ISM; the inner and outer shocks of their winds can be seen in the upper right and lower left of Fig. 2. In Fig. 3 we show the averaged temperature along the line of sight at the same point in time. Some of the shocks of the wind bubbles can be seen but the hot bubble around Sgr A\* is clearly dominant. Of course, after only 8 yrs, the simulation is far from any equilibrium.

### 4.2 Later time results

It takes  $\sim 25$  yrs for the O star winds to fill the central  $(1'')^3$  of the Galaxy. As more gas enters the volume, the average column density increases and gas continues to pile up near the black hole. However, the gas-fill is still patchy and the calculation has still not converged since the central stars have completed approximately only a single orbit. Thus, the simulation was continued for more than 500 yrs; at this point the gas density surrounding Sgr A\* has saturated due to the high temperature of the compressed gas and periodic purging by stars passing close to the black hole. By 500 yrs, the volume around Sgr A\* dominates the column density and individual wind blown bubbles are no longer clearly seen (Fig. 4).

We calculated emission (using MEKAL) and absorption (using CLOUDY, Ferland (2000)) coefficients for

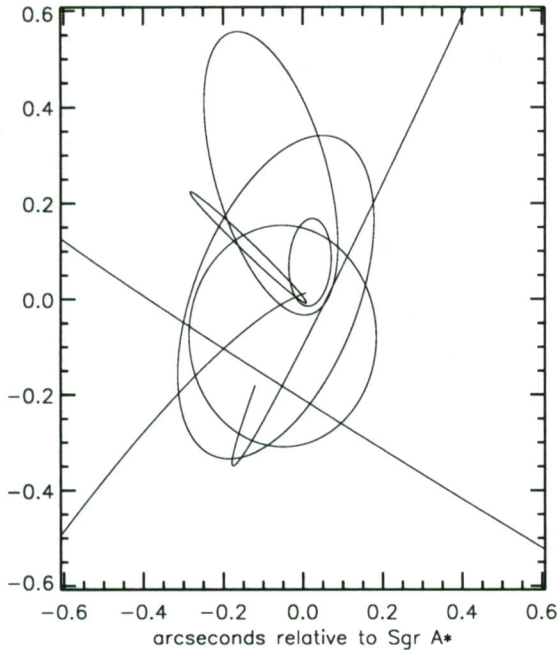


Figure 1: The projected orbits of the 8 O stars for the volume of the simulation ( $1.2''$  on a side). The start of the orbits is at zero time and corresponds to 1989. For some unknown reason, the orbit of S0-3 (the star that cuts completely across the field of view) does not match that plotted in Ghez et al. (2004), Fig. 2

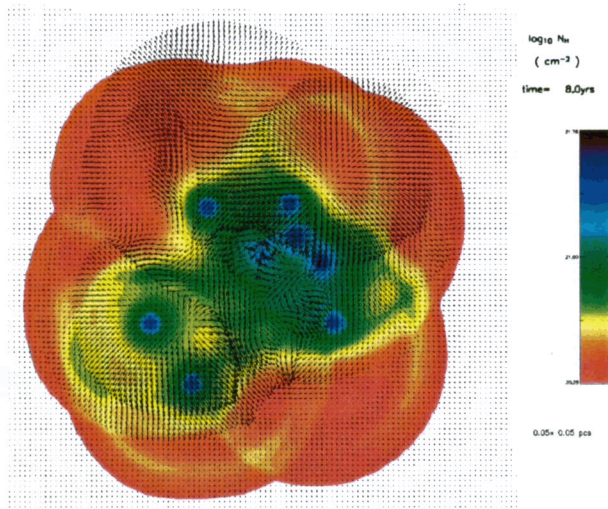


Figure 2: The column density along the line of sight 8 yrs into the simulation. Wind-wind shocks and the gas pile up at Sgr A\* can be seen.

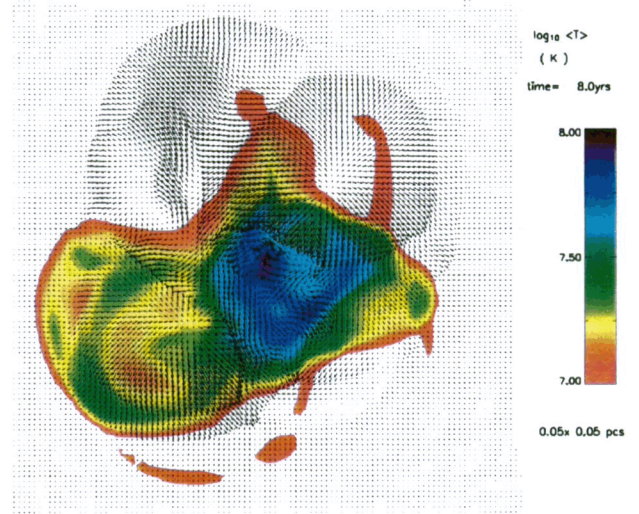


Figure 3: The spatially averaged temperature along the line of sight 8 yrs into the simulation. A hot cavity surrounding Sgr A\* can be seen. Note that blue is hot and red is cold.

each cell at 569 yrs. Then we used a ray-tracing program to solve the radiation-transfer equation along the line of sight to produce a synthetic 2-10 keV X-ray image and thus estimate the X-ray photon index, luminosity, and spectrum. In Fig. 5 we show the resulting intrinsic and absorbed spectrum at 569 yrs. It can be seen that due to the high column density towards the GC, X-ray emission below  $\sim 2$  keV is likely to be heavily absorbed. The intrinsic 2-10 keV luminosity is  $3.7 \times 10^{32}$  erg sec $^{-1}$  while the absorbed luminosity is  $2.4 \times 10^{32}$  erg sec $^{-1}$ . The photon index was found to be  $\sim 1.4$ . In Fig. 6 we show the synthetic X-ray image. The emission from near Sgr A\* is extended on the order of  $\sim 0.1''$  or  $\sim 10^4 R_g$ .

## 5 Discussion and summary

From CHANDRA observations, the estimated intrinsic 2-10 keV luminosity of Sgr A\* is  $2.4 \times 10^{33}$  ergs sec $^{-1}$ . Assuming a power-law model, the observed photon index is between 1.8 and 4.0 with a best fit value of 2.7 (Baganoff et al., 2003). Initial 3D simulations of 8 orbiting O8 stars in the central  $1.5''$  of the Galaxy show that their winds result in an absorbed luminosity of  $2.4 \times 10^{32}$  erg sec $^{-1}$ . Thus it appears that at least 10% of the CHANDRA point source is due to emission from fairly far away from the putative black hole's event horizon. If there are more O stars in the



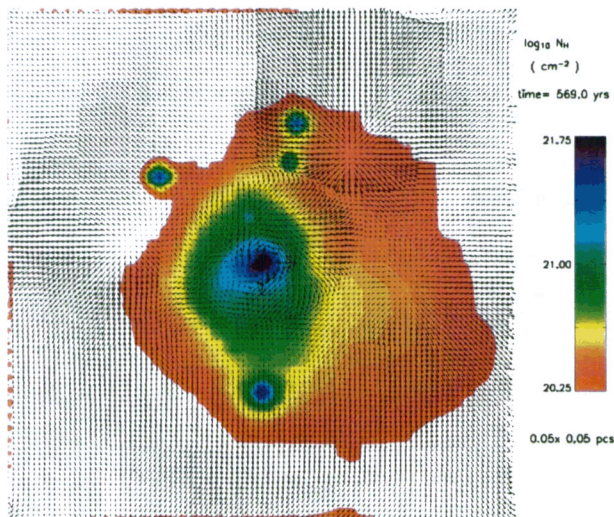


Figure 4: The column density at 569 yrs. Sgr A\* dominates the column. At the edges of the volume, the effects of imperfect outflow boundary conditions can be seen.

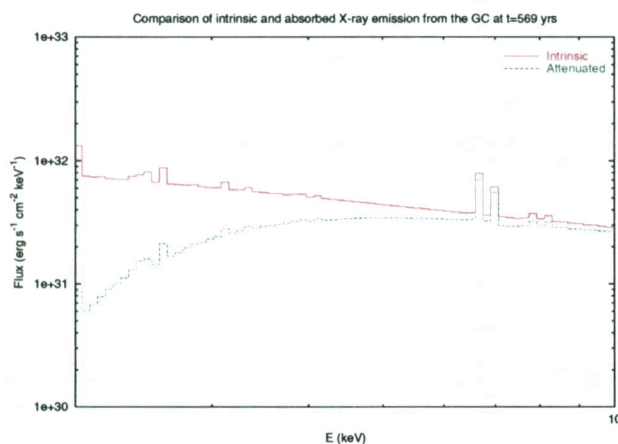


Figure 5: The predicted 2-10 keV X-ray spectrum for the gas distribution shown in Fig. 4. The column towards the GC is taken to be  $10^{23} \text{ cm}^{-2}$ . To compare to the results of Baganoff et al. (2003), these results need to be convolved with the detector response.



Figure 6: A truecolor map (with red=2-3 keV, green=3-5 keV, and blue=5-10 keV) of the X-ray emission from the gas distribution shown in Fig. 4. Sgr A\* dominates the emission although some of the individual stars can still be seen.

central milliparsecs or if their winds are stronger, it is possible that all of the CHANDRA point source is in fact extended emission on the scale of  $\sim 0.1''$ . This would imply that only the flared emission is coming from near the black hole event horizon and accretion models for Sgr A\* which predict constant significant X-ray emission from near the black hole may need to be revised.

## Acknowledgments

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